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TOWS

TERABIT OPTICAL WIRELESS SYSTEM

# The optical spectrum and Tb/s wireless systems in the 6G era


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# Outline

- TOWS 6G Vision
- Industrial eco system
- TOWS project
- 4G, 5G and 6G
- Use Cases
- Highlights
  - Hardware
  - Systems
  - Architecture
  - Demos
- Future directions

# Terabit Bidirectional Multi-user Optical Wireless System (TOWS) for 6G LiFi

## Vision

Our vision is to develop and experimentally demonstrate multiuser Terabit/s optical wireless systems that offer capacities at least two orders of magnitude higher than the current planned 5G optical and radio wireless systems, with a roadmap to wireless systems that can offer up to four orders of magnitude higher capacity.

*First, UK 6G project; paradigm shift from radio to optical, indoor*

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*April 2019 – March 2024, £6.6m project*

# Industrial partners

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| | | |
|---|---|---|
| **Vendors** | Devices | IQE; Compound Semiconductor Technologies; Compound Semiconductor Centre |
| | Optical Systems | ADVA Optical Networking; pureLiFi; zinwave; USHIO |
| | Communication Networks and Systems | Cisco; Nokia; Hewlett Packard |
| **Operators** | Mobile Network | orange; Deutsche Telekom |
| | Wired Network | BT; Jisc |
| **Service providers** | Media | BBC; Microsoft |
| | Software, manufacturing | babcock trusted to deliver; Airbus Group |

# Drivers and future directions

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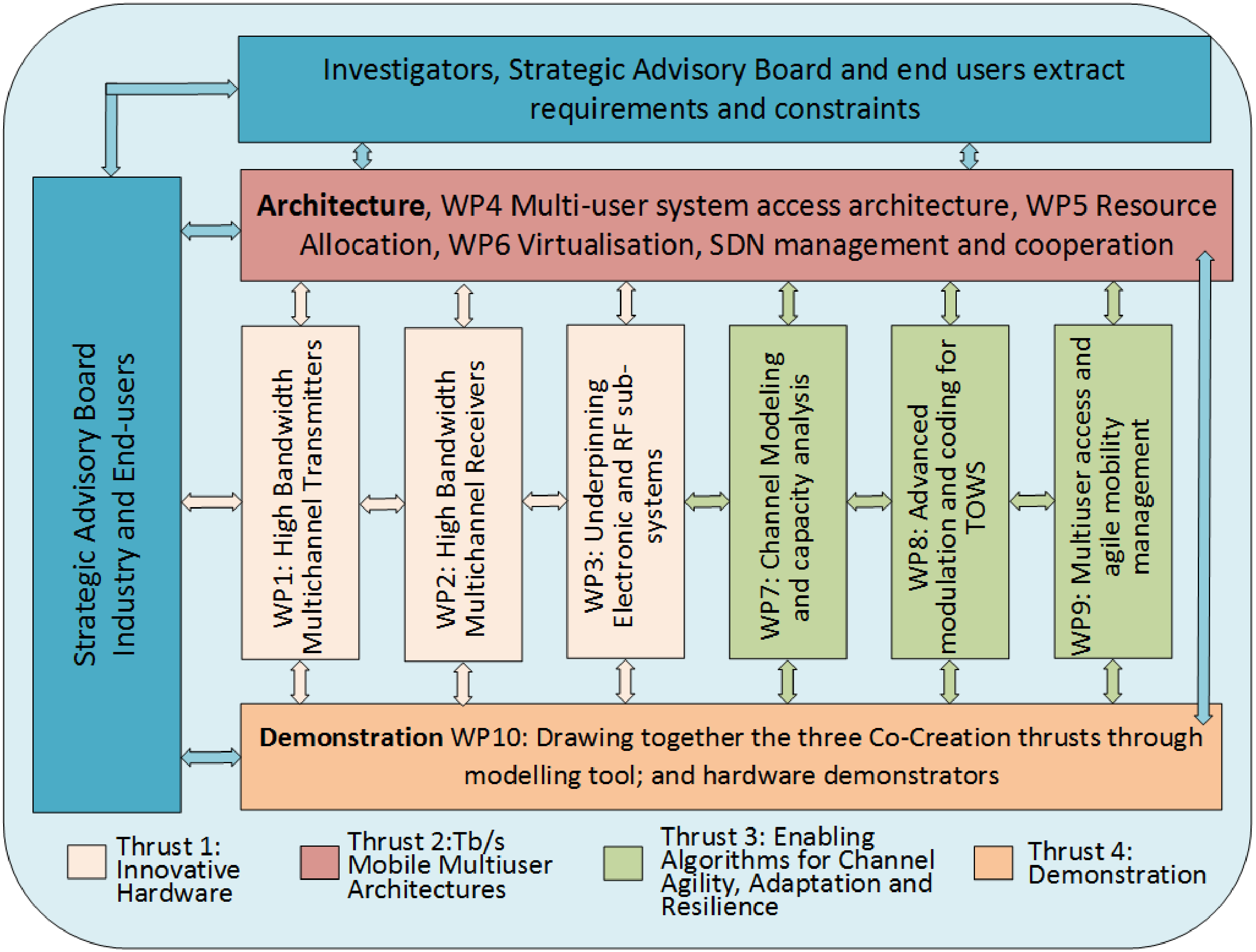
- Internet traffic is projected to grow by factors of 30x and 1000x in 10 and 20 years respectively.
- Mobile data is the fastest growing traffic strand, currently growing at 60% per year leading to a projected growth of over 10,000x in 20 years.
- Despite the tremendous improvements due to the small cell concept and the allocation of new radio frequency (RF) spectrum in 5G, it is inevitable that the RF part of the electromagnetic spectrum will not be sufficient to drive the 4th industrial revolution.
- This highlights the need for a step change in approach via new technologies that are able to provide communication efficiently at parts of the spectrum other than the 100GHz of RF spectrum currently in use.
- Current estimates are that 80% of all mobile connections originate and terminate indoors.
- A potential disruptive solution is optical wireless (OW) communication.

# TOWS project



# Mobile Radio and Optical Wireless Data Rates

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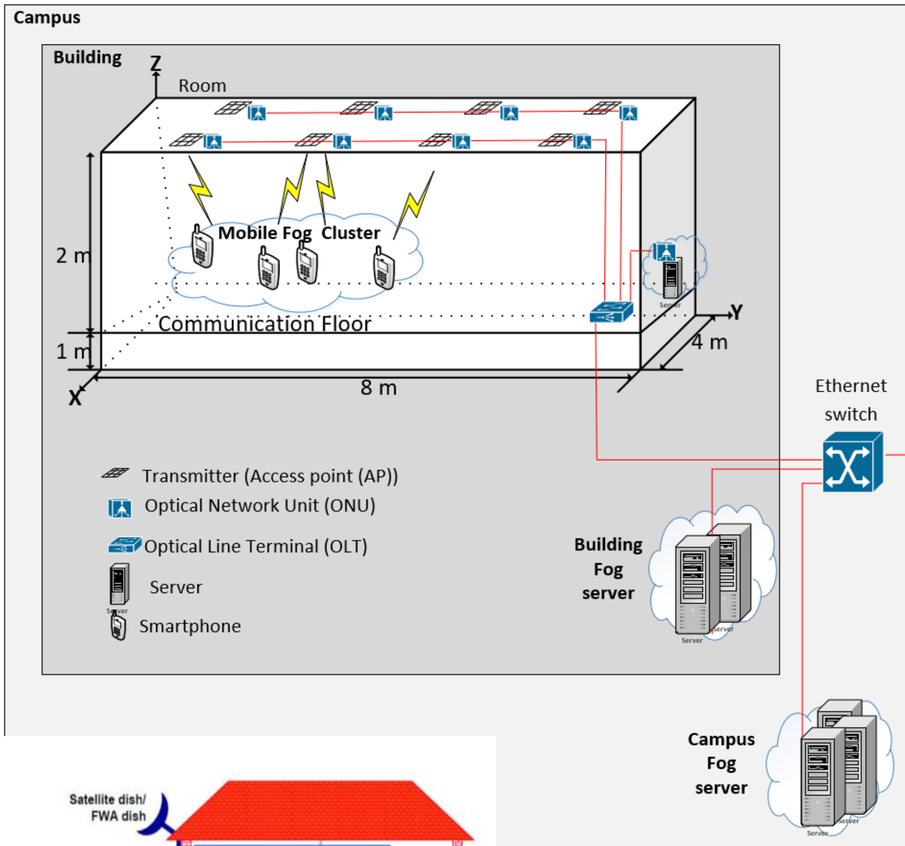
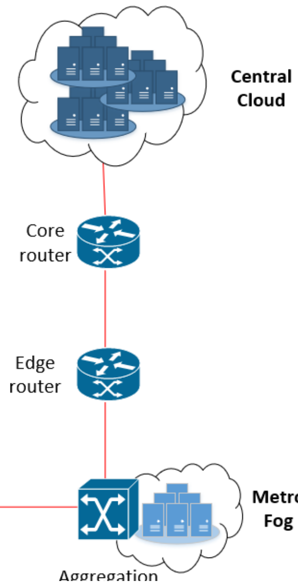
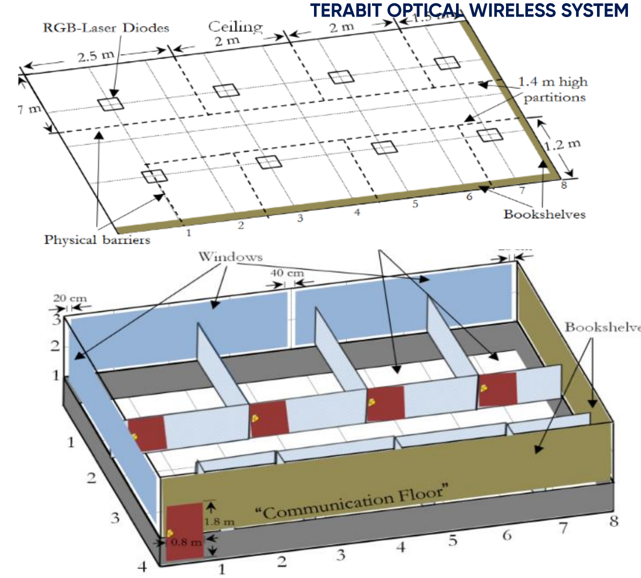
| Mobile base station | Data rate | Mobility |
|---|---|---|
| 4G | 100Mb/s – 300Mb/s | High |
| 5G | 10Gb/s | Small Cells |
| IEEE 802.11 bb (optical wireless) | 10Gb/s peak | WiFi size cells |
| IEEE 802.15.13 (Multi-Gigabit/s Optical Wireless Communications) | 10Gb/s (July 2019) | LoS, 200m |
| IEEE 802.15.7r1 (Optical Camera Communication (OCC)) | 100 Mb/s | High |
| Experimental Optical Wireless | 40Gb/s | Beam steering |
| TOWS | 1Tb/s – 10Tb/s | Indoor mobility, 50m$^2$ per access point; 2.5Gb/s - 50Gb/s per user |

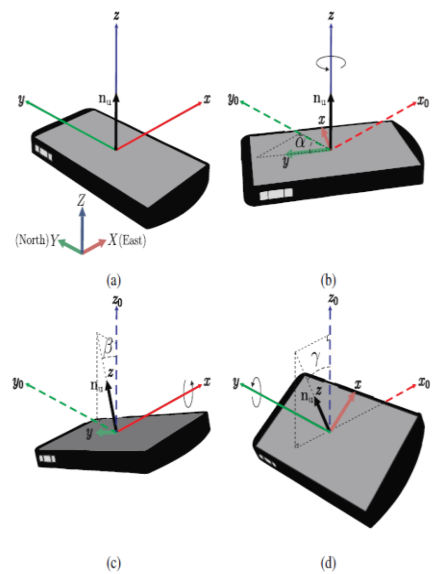
- TOWS BBC use case:
  - Studio 22m x 14m or 30m x 33m
  - Uncompressed UHDTV, 23Gb/s per camera
  - 12 to 20 cameras in studio; up to 460Gb/s; 4-5 cameras used sometimes)

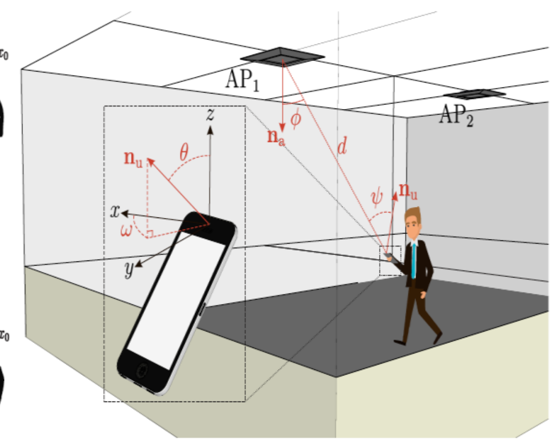
# TOWS architecture and sub-systems

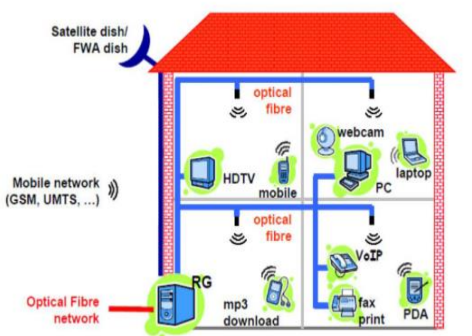


# TOWS architecture and sub-systems

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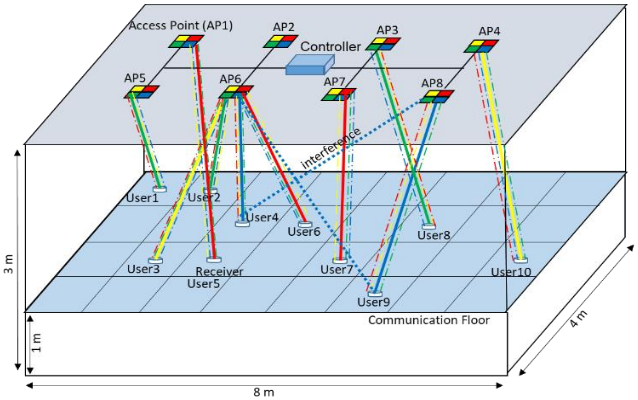
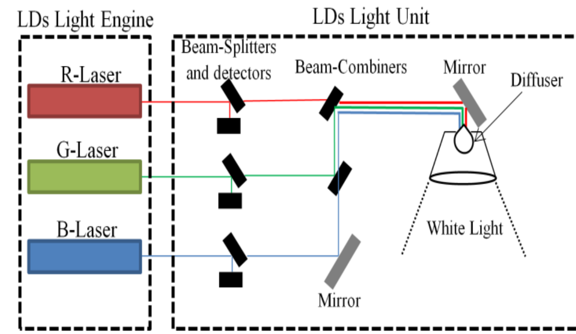
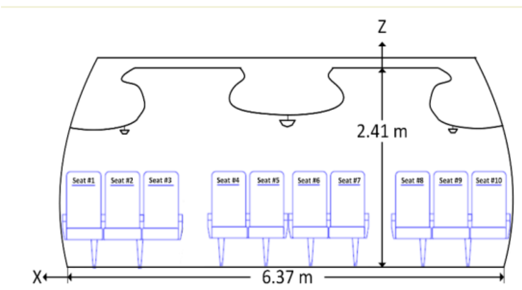
Indoor



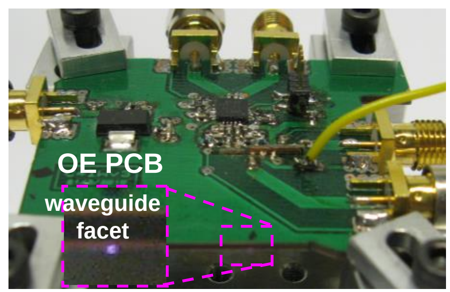

Multiple access



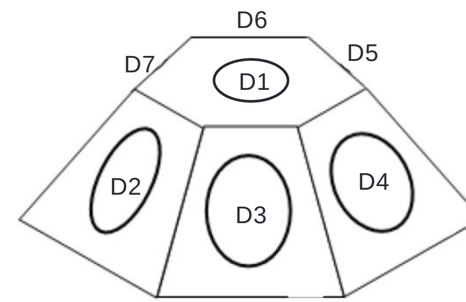

Transmitter module



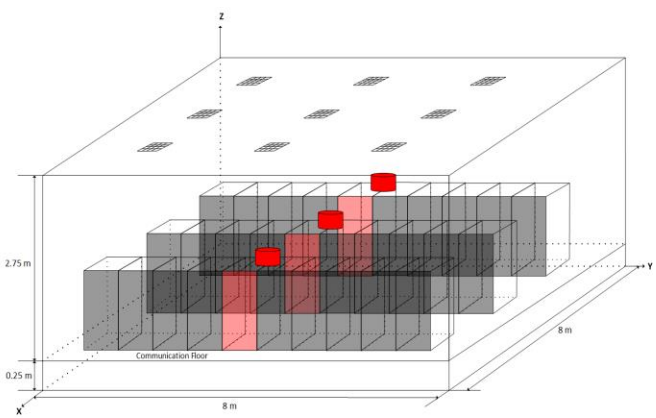

In cabin



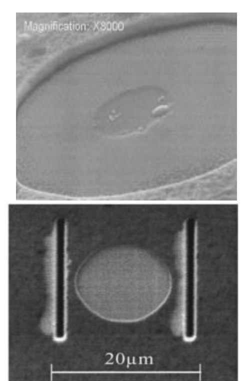

Integration

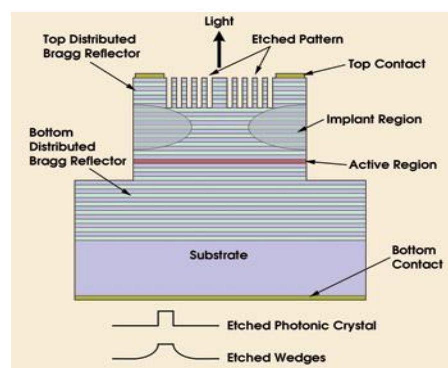



Angle diversity receiver




In data centre




Surface relief and polarisation pinned VCSELs for beam and spectral control

# Hardware: Current studies

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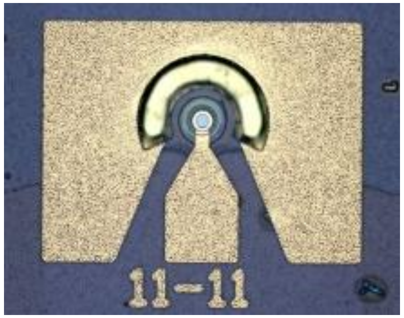
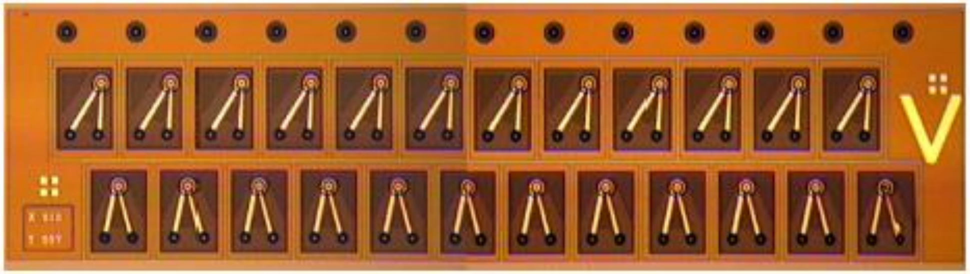
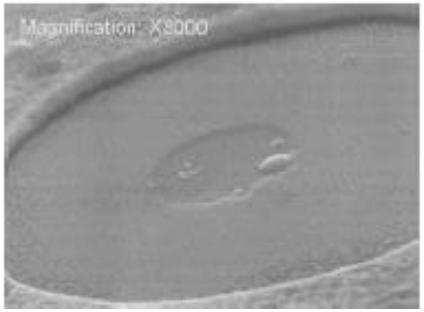
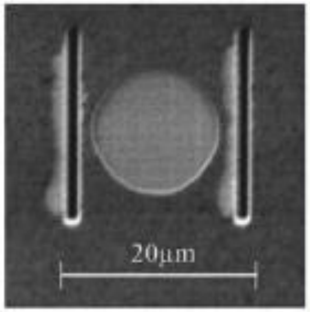
Current work:

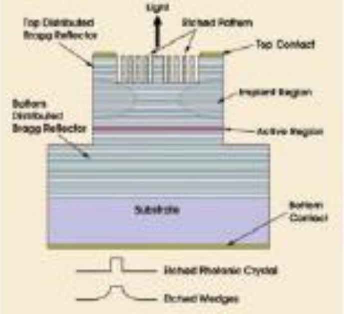
- Transmitter and Receiver optics
- room coverage, AP distribution
- high speed VCSEL-based links
- beam steering concepts
- system implications





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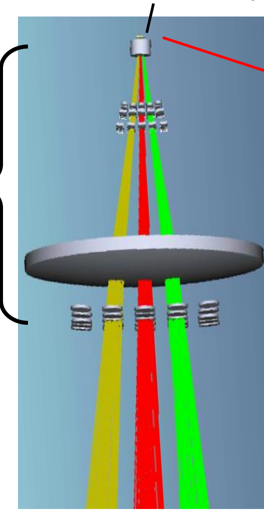
# Hardware: Transmitter optics

- work on the design of Tx optics system for TOWS system:
  - 1 $m^2$ covered with a 5 × 5 VCSEL array
  - beam homogenisation at the floor plane
    → uniform SNR
  - minimise beam interference (direct path)
  - eye safety considerations

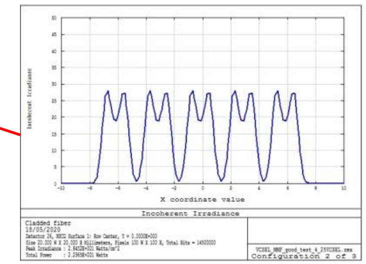
→ formation of high-capacity communication cells

5 × 5 VCSEL array

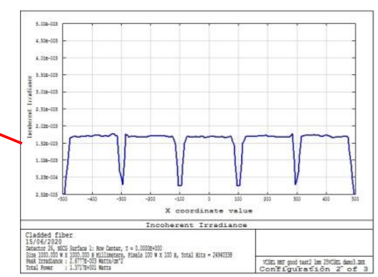
beam homogenisation system



VCSEL output intensity

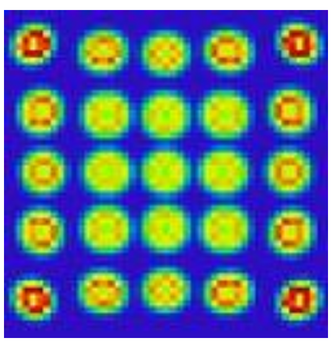


floor intensity



~ 86% intensity uniformity

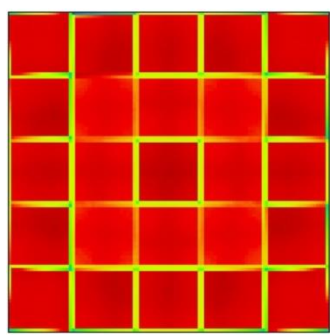
1 m



1 m

5 × 5 VCSEL array single lens system

beam homogenisation system



1 m

1 m

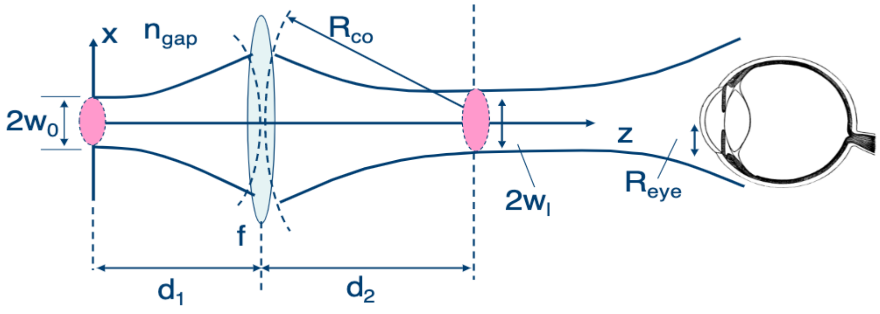
5 × 5 VCSEL array beam homogenisation

# Hardware: Laser safety

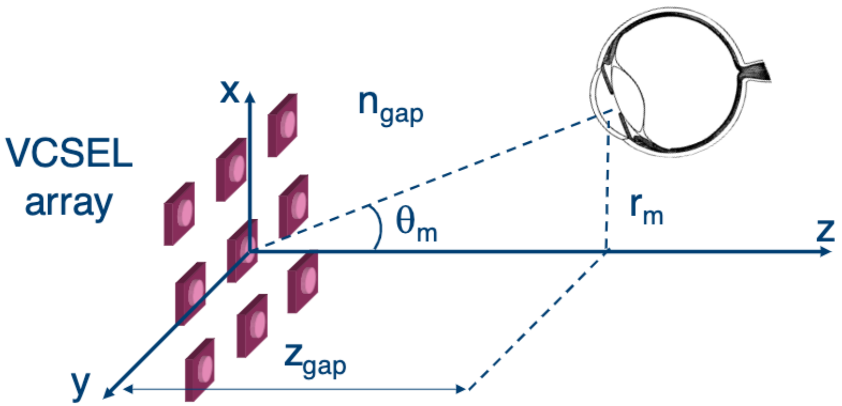
**Highlights**:

A generalized framework for laser safety analysis has been developed where the maximum permissible transmit power of a laser source ensuring both skin and eye safety, is derived for various cases including:

1. Single mode Gaussian/non-Gaussian beams
2. Multi-mode beams (through measurements)
    - Hermitte-Gaussian beam
    - Laguerre-Gaussian beam
3. Laser with lens
    - System of lenses
    - Thin lens
4. Laser with diffuser
    - Lambertian pattern diffusers
    - Uniform pattern diffusers
5. Laser array
    - Laser array with a collimated beam
    - Laser array with diverged beams




Eye safety analysis for beam propagation through a lens.



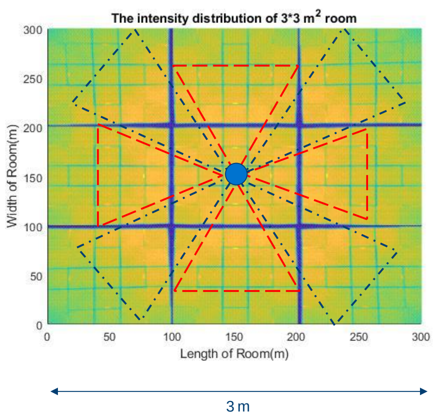

Eye safety analysis for VCSEL arrays.

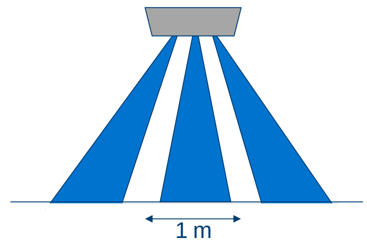
**Publications:**
M. D. Soltani, *et al.*, "Laser-Based Optical Wireless Communication: Design and Safety"

# Hardware: Room coverage

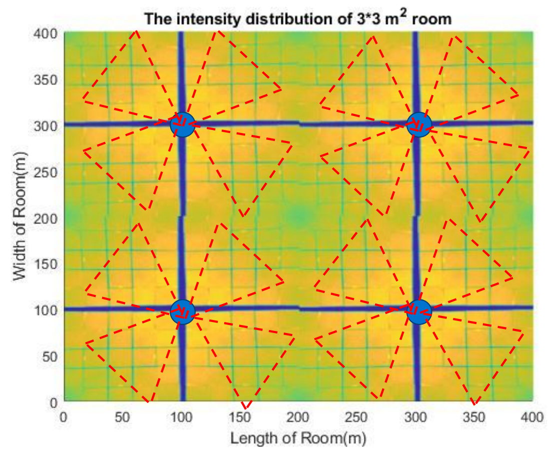
- application in the room for coverage (3 × 3 $m^2$)

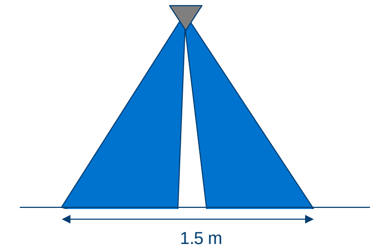
→ distribution of access points (APs)



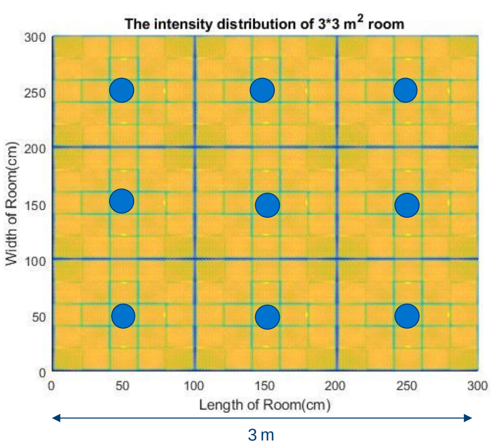



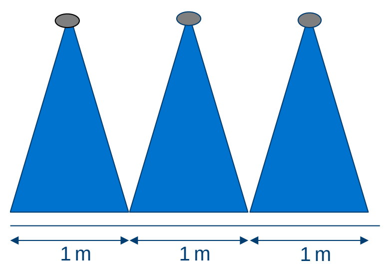

| Items | Parameter |
|---|---|
| No. Access Point | 1 |
| Transmitter/ AP | 9 |
| Covered area % | 91% |




| Items | Parameter |
|---|---|
| No. Access Point | 4 |
| Transmitter/ AP | 4 |
| Covered area % | 92% |

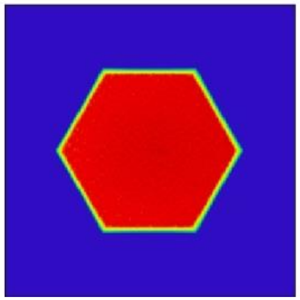


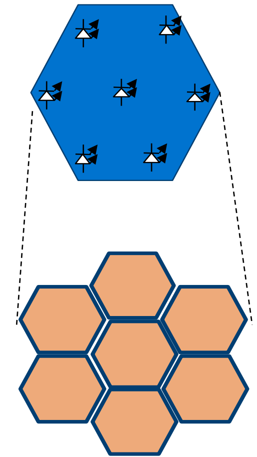




| Items | Parameter |
|---|---|
| No. Access Point | 9 |
| Transmitter/ AP | 1 |
| Covered area % | 96% |

Alternative shaping of output beam

single VCSEL beam shaping

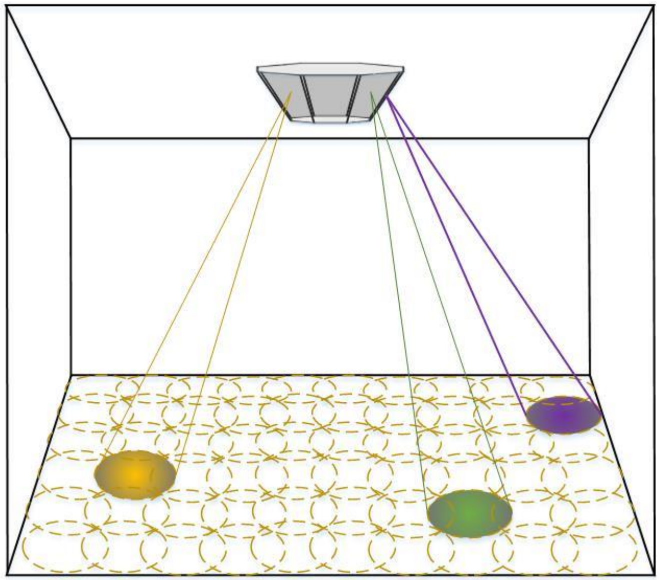




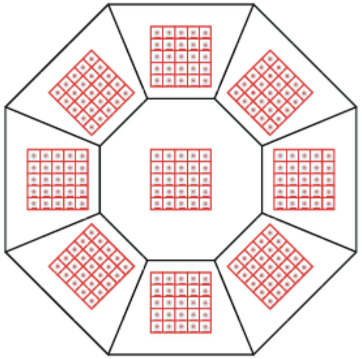
# System: Terabit optical wireless system

**Highlights**:

- A novel double tier access point (AP) architecture based on **array of arrays** of vertical cavity surface emitting lasers (VCSELs) is proposed.
- The AP covers the entire indoor area.
- The AP provides an aggregate data rate beyond 1 Tb/s (at least 10 Gb/s per beam).
- The inter-beam interference is minimized.
- This design supports multi-user access.
- This design is subject to the optical power emission limit for VCSELs due to eye safety.



Indoor access cells



An array of arrays of VCSELs (top view).

**Publications:**
E. Sarbazi, *et al.*, "A Tb/s Indoor Optical Wireless Access System Using VCSEL Arrays", presented at PIMRC 2020.

# System: Spatial distribution of the data rate over the coverage area

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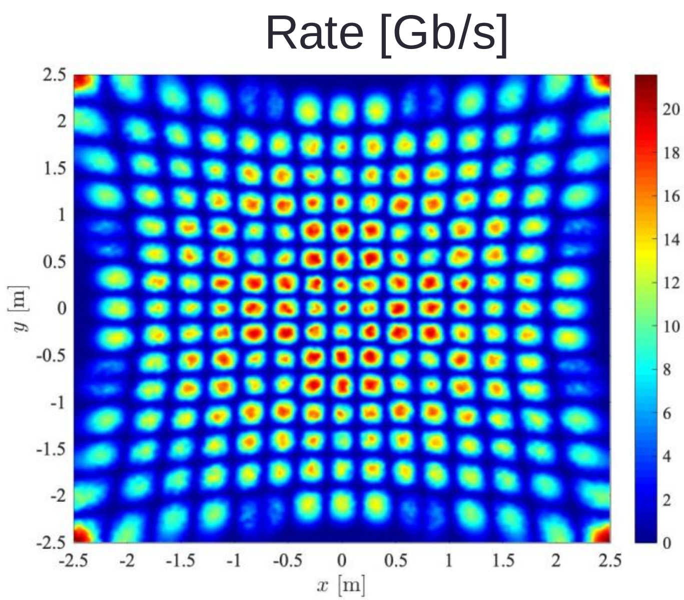
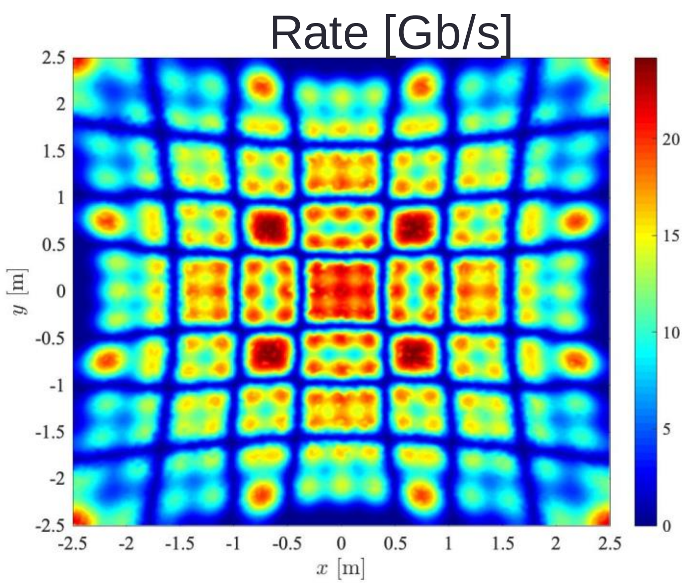
**System parameters:** Link distance: 3 m; Number of VCSELs: 225; VCSEL output power: 10 mW; VCSEL bandwidth: 10 GHz; Detector effective area: 2 cm$^2$




**Individual beams:**
Data rates of 10 to 20 Gb/s are achieved at the beam spot centres.
The AP delivers an aggregate data rate of beyond $225 \times 10$ Gb/s = 2.25 Tb/s.

**Static clusters:**
Clustering helps to improve the spot-edge rate performance. Each cluster is composed of a number of neighbouring beam spots.

**Publications:**
E. Sarbazi, *et al.*, “A Tb/s Indoor Optical Wireless Access System Using VCSEL Arrays”, PIMRC 2020.

# System: Terabit optical wireless backhaul

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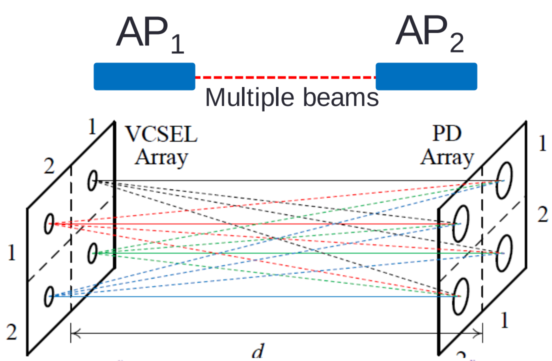
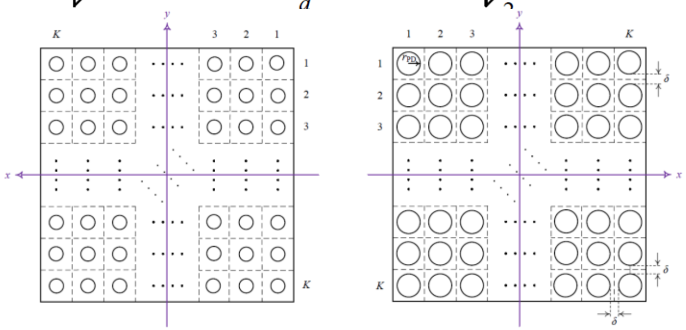
**Highlights**:

- A MIMO optical wireless backhaul system using VCSEL arrays is proposed.
- A 25 × 25 system using 5 × 5 arrays achieves an aggregate data rate of more than 1 Tb/s.

**System parameters:**
Link distance: 2 m
VCSEL output power: 1 mW
VCSEL bandwidth: 20 GHz
Effective area per detector: 0.5 cm2
$w_0$ is the effective beam waist radius

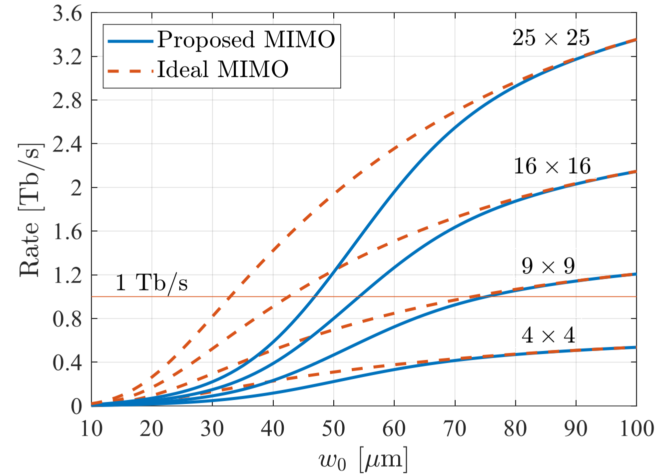


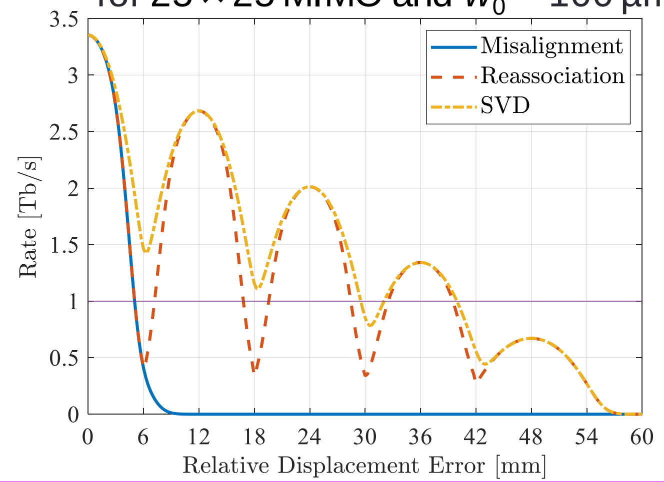
(a) $K \times K$ VCSEL array

(b) $K \times K$ PD array

Perfect Alignment




Misalignment
for 25 × 25 MIMO and $w_0$ = 100 μm




**Publications:**
H. Kazemi, *et al.*, “A Tb/s Indoor Optical Wireless Backhaul System Using VCSEL Arrays”, presented at PIMRC 2020.

# System: High-speed operation

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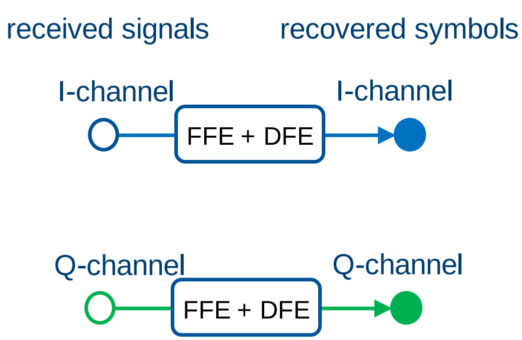
- work on advanced modulation formats and equalization methods

  → new equalizer structure for CAP-based optical links : CAP equalizer

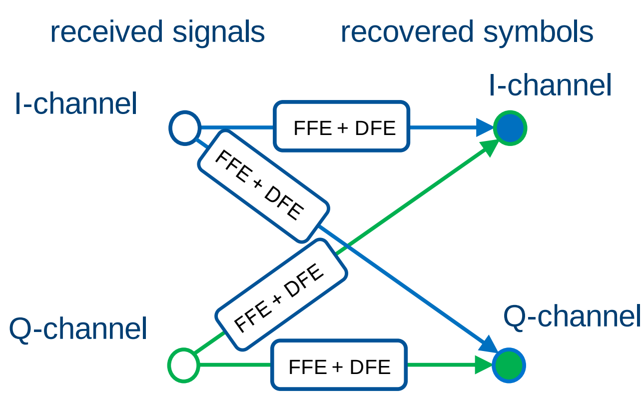
  → demonstrated in VCSEL-based MMF link : 124 Gb/s achieved with 25 GHz VCSEL

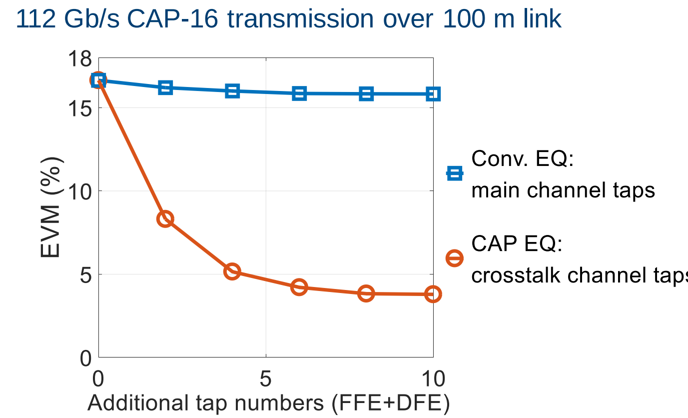
  → low complexity implementation – similar to conventional FFE/DFEs

conventional equalizer




CAP equalizer



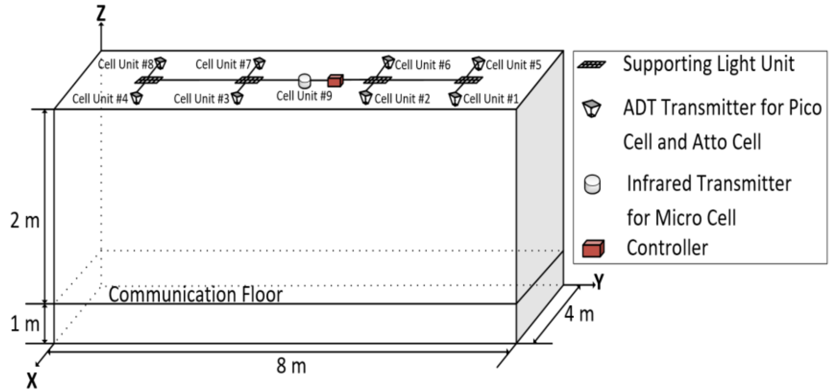



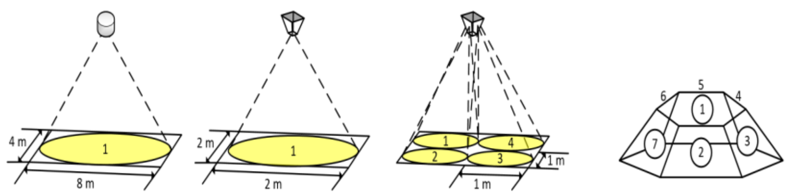

→ similar concepts to be applied to TOWS systems to improve link capacity

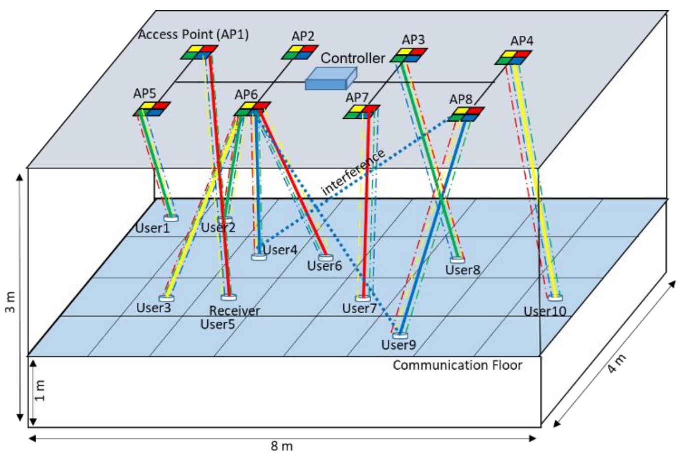
X. Dong, et al., JLT, vol. 37, pp. 5937-5944, 2019

X. Dong, et al., in ECOC, pp. 1-3, paper P.20, 2019

# Architecture: Resource allocation




Alsulami, O. Z., Alahmadi, A., Saeed, S. O. M., Mohamed, S.H., El-Gorashi, T.E.H., Alresheedi, M.T. and Elmirghani, J.M.H., "Optimum resource allocation in optical wireless systems with energy efficient fog and cloud architectures," Philosophical Transactions of the Royal Society A, vol. 378, No. 2169, pp. 1-29, March 2020.

- $SINR_{u,r}^{c,a,\lambda} = \frac{Signal}{Interference+Noise}$
- Signal: $Sig_{u,r}^{c,a,\lambda} = (R \;\; Pt_{u,r}^{c,a,\lambda} \;\; h_{u,r}^{c,a,\lambda})^2$
- The preamplifier noise: $\sigma_{Rx} = N_{pr} B_e$
- The background light shot noise: $\sigma_{u,r}^{cc,b,\lambda} = 2e\left(R \;\; Pt_{u,r}^{cc,a,\lambda} \;\; h_{u,r}^{cc,a,\lambda}\right) B_o B_e$
- $SINR_{u,r}^{c,a,\lambda} =$

$$\frac{Sig_{u,r}^{c,a,\lambda} \;\; S_{u,r}^{c,a,\lambda}}{\sum_{cc\in C}\sum_{\substack{b\in\mathcal{A}\\ b\neq a}}\sum_{\substack{iu\in\mathcal{U}\\ iu\neq u}}\sum_{ir\in\mathcal{B}} Sig_{iu,ir}^{cc,b,\lambda} \; S_{iu,ir}^{cc,b,\lambda} + \sum_{cc\in C}\sum_{\substack{b\in\mathcal{A}\\ b\neq a}} \sigma_{u,r}^{cc,b,\lambda}\left[1-\sum_{\substack{iu\in\mathcal{U}\\ iu\neq u}}\sum_{ir\in\mathcal{B}} S_{iu,ir}^{cc,b,\lambda}\right]+\sigma_{Rx}}$$

The MILP model is subject to:

- $\sum_{u\in\mathcal{U}}\sum_{r\in\mathcal{B}} S_{u,r}^{c,a,\lambda} \leq 1 \qquad \forall c\in C, \forall a\in\mathcal{A}, \forall\lambda\in\mathcal{W}$

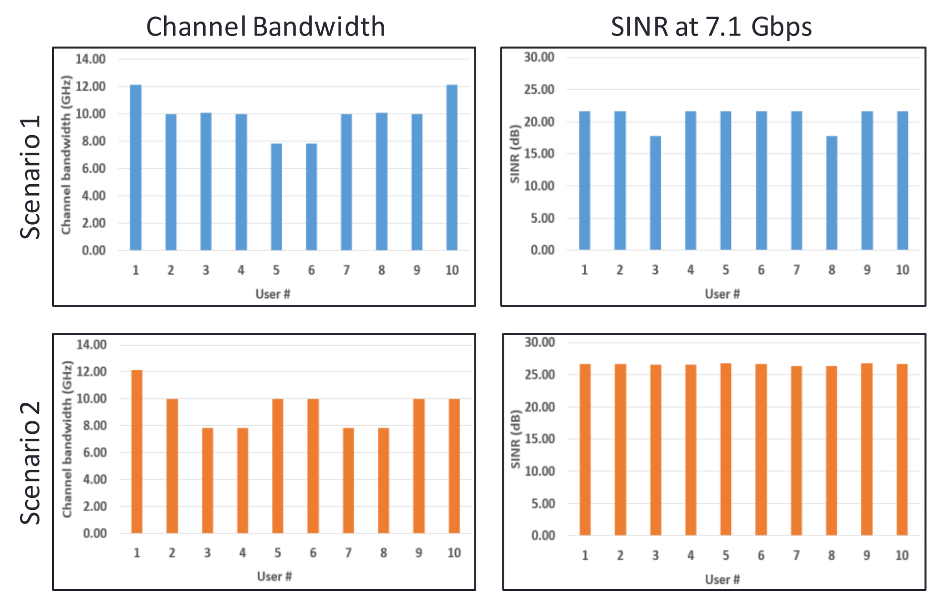
(To ensure that a wavelength belonging to an AP is only allocated once)

- $\sum_{c\in C}\sum_{a\in\mathcal{A}}\sum_{\lambda\in\mathcal{W}}\sum_{r\in\mathcal{B}} S_{u,r}^{c,a,\lambda} = 1 \qquad \forall u\in\mathcal{U}$

(To ensure all users are assigned to one cell unit, access point, one wavelength and one branch)

- $SINR_{u,r}^{c,a,\lambda} \geq 10^{\frac{36}{10}} \qquad \forall u\in\mathcal{U}, \forall c\in C, \forall a\in\mathcal{A}, \forall\lambda\in\mathcal{W}, \forall r\in\mathcal{B}$

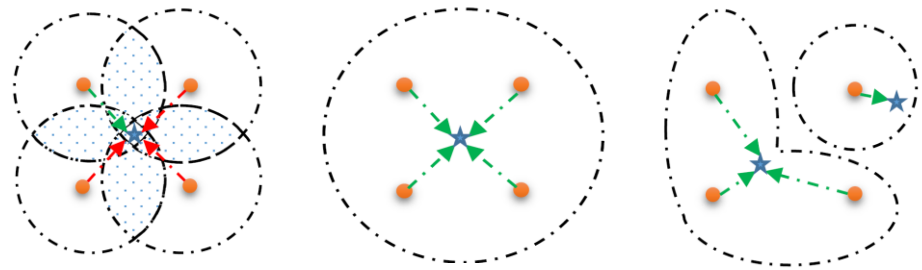
(To ensure the SINR of each user does not go below 15.6 dB)



# Multiuser architectures

## Optical Cell Formation

- Full connectivity design
- Network centric design
- User centric design: optimal and sub optimal UC approach



Multi-APs Network Centric User Centric

Cell formation

## Interference Management

- Precoding schemes

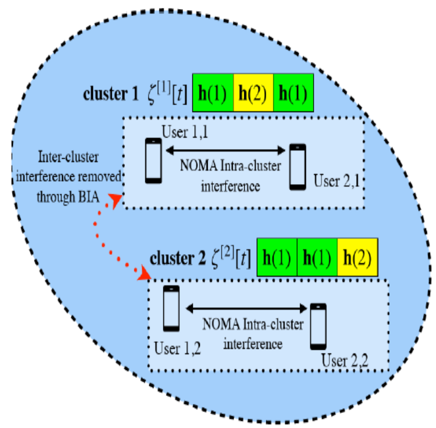
  ZF, MSE, MMSE and RS

- Power control and Blind schemes

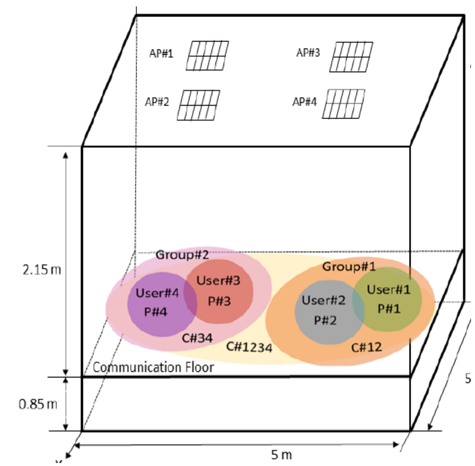
  NOMA and BIA

- Hybrid schemes

  HRS, BIA-RS, BIA-NOMA and H-BIA




A. BIA-NOMA




B. HRS

Hybrid schemes

# Multiuser architectures

## BBC studio

- Each camera equipped with transmitter using VCSEL covers an area that can reach up to 1.45 m x 1.45 m at 11m distance.

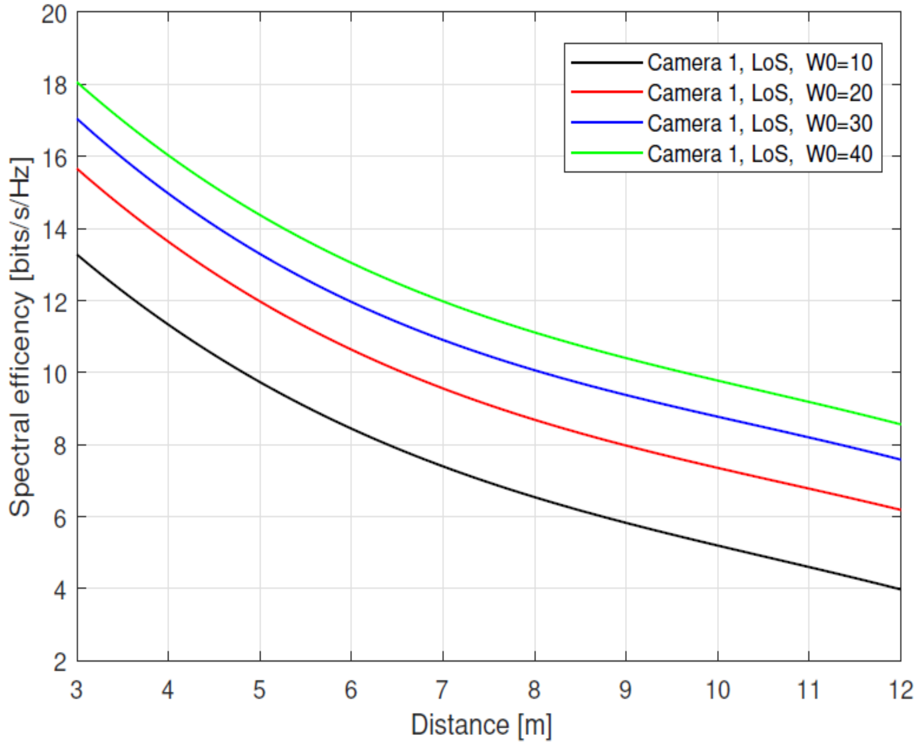



Fig. 2. SE vs distance.

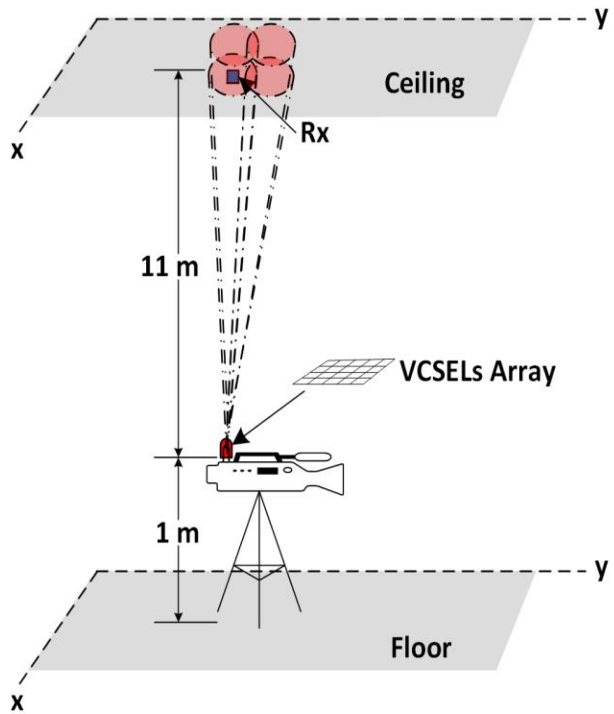
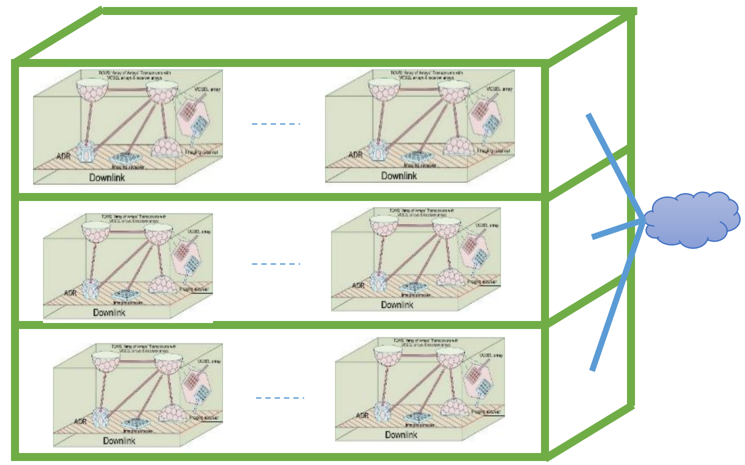



Fig. 1. A use case.

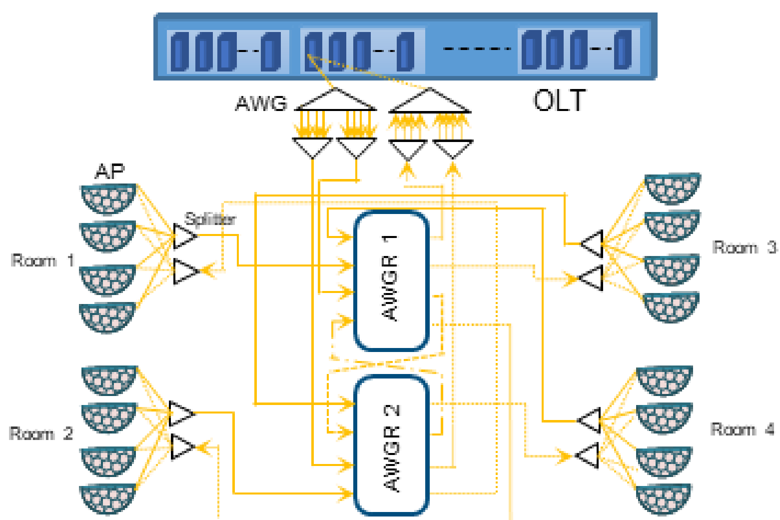
# Architecture: Backhaul fibre network

TERABIT OPTICAL WIRELESS SYSTEM

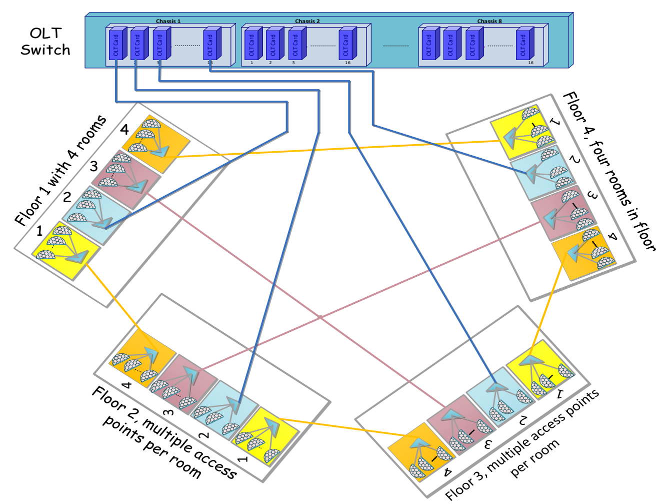
- Purpose:
  - Access Point (AP) to AP wired links within a room for **device to device** communication
  - Room to room and floor to floor links for user **Mobility and for Aggregating processing capacity** from user devices, IoT devices and distributed servers



- Proposed PON-based Networks:
  - WDM-TDM architecture (uses AWGRs and tunable lasers)
  - Point-to-Point single wavelength architecture (use APs for routing)




WDM-TDM architecture




Point-to-Point architecture

# Architecture: Backhaul fibre network modelling

TERABIT OPTICAL WIRELESS SYSTEM

- Developed a MILP Model to Optimise Flow Scheduling and Routing between APs to evaluate the impact of network topology on the performance and energy efficiency
- Comparison with Fat-tree and Spine-leaf
- MILP Objective: Minimise the energy consumption (E) or the latest completion time (M) of data transfer

$$\min \left[ E + Q \sum_{s,d \in \mathbb{R}, t \in \mathbb{T}, s \neq d} (t\, \delta_{sdt}) \right], \quad \min \left[ M + Q \sum_{s,d \in \mathbb{R}, t \in \mathbb{T}, s \neq d} (t\, \delta_{sdt}) \right].$$

- Under several constraints (e.g. flow conservation, traffic scheduling, completion time calculation)

$$\sum_{v \in \mathbb{G}_u} \chi^{sd}_{uvwt} - \sum_{v \in \mathbb{G}_u} \chi^{sd}_{vuwt} = \begin{cases} \delta_{sdt} & u = s \\ -\delta_{sdt} & u = d \\ 0 & otherwise, \end{cases}$$

$$\forall s, d \in \mathbb{R}, s \neq d, u \in \mathbb{G}, w \in \mathbb{W}, t \in \mathbb{T}.$$

$$\sum_{t \in \mathbb{T}} \delta_{sdt} = \Delta_{sd}; \forall s, d \in \mathbb{R}, s \neq d$$

$$\Omega_{uvwt} = D\,(t-1) + \frac{\psi_{uvwt}}{C_{uvw}}, \quad \text{and}$$

$$\tau_{uvwt} \leq L\,\Gamma_{uvwt}, \quad \text{and}$$

$$\tau_{uvwt} \leq \Omega_{uvwt}, \quad \text{and}$$

$$\tau_{uvwt} \geq \Omega_{uvwt} - L\,(1 - \Gamma_{uvwt}), \quad \text{and}$$

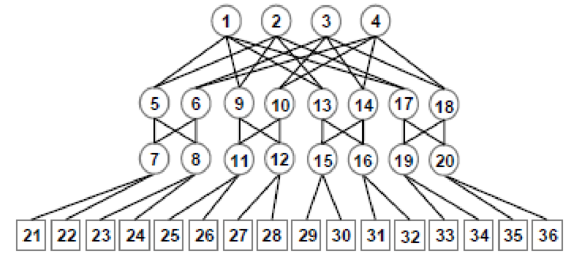
$$\forall u \in \mathbb{G}, v \in \mathbb{G}_u, w \in \mathbb{W}, t \in \mathbb{T}.$$

$$M \geq \tau_{uvwt}, \quad \text{and}$$

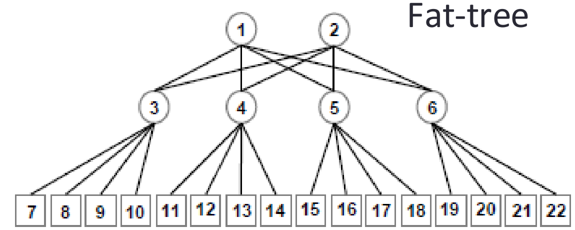
$$M \leq \tau_{uvwt} + L\,[1 - Z_{uvwt}], \text{and}$$

$$\forall u \in \mathbb{G}, v \in \mathbb{G}_u, w \in \mathbb{W}, t \in \mathbb{T},$$

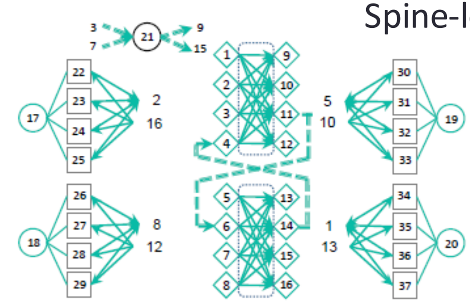
$$\sum_{i \in \mathbb{G}, v \in \mathbb{G}_u, w \in \mathbb{W}, t \in \mathbb{T}} Z_{uvwt} = 1.$$



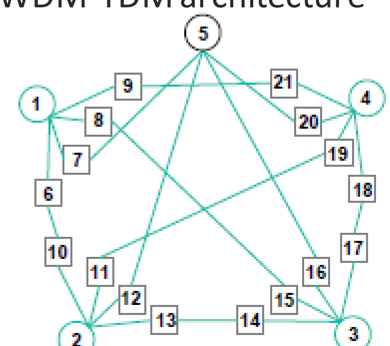
Fat-tree



Spine-leaf



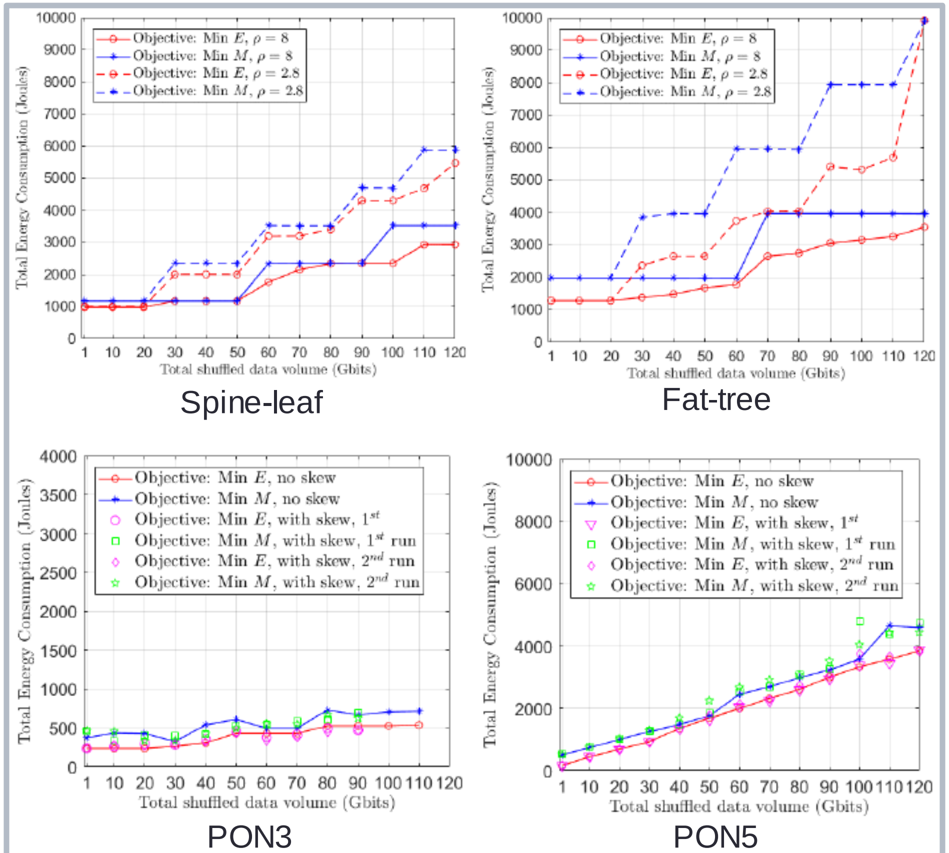
WDM-TDM architecture



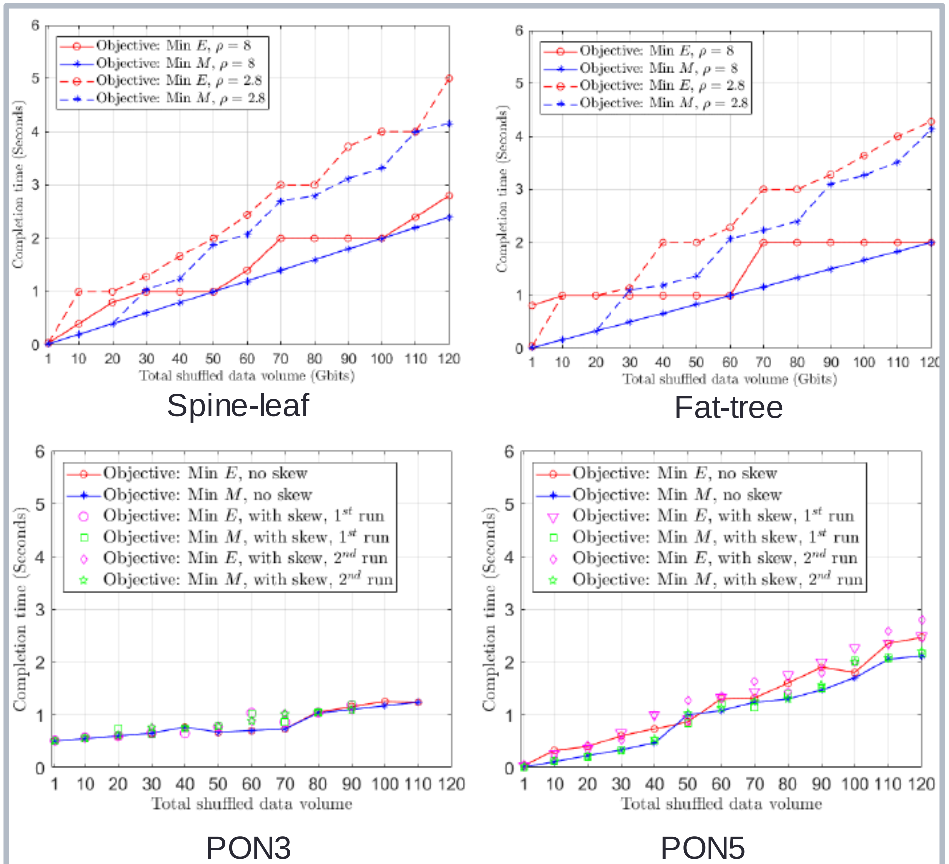
Point-to-Point architecture

# Architecture: Backhaul fibre network

TOWS
TERABIT OPTICAL WIRELESS SYSTEM



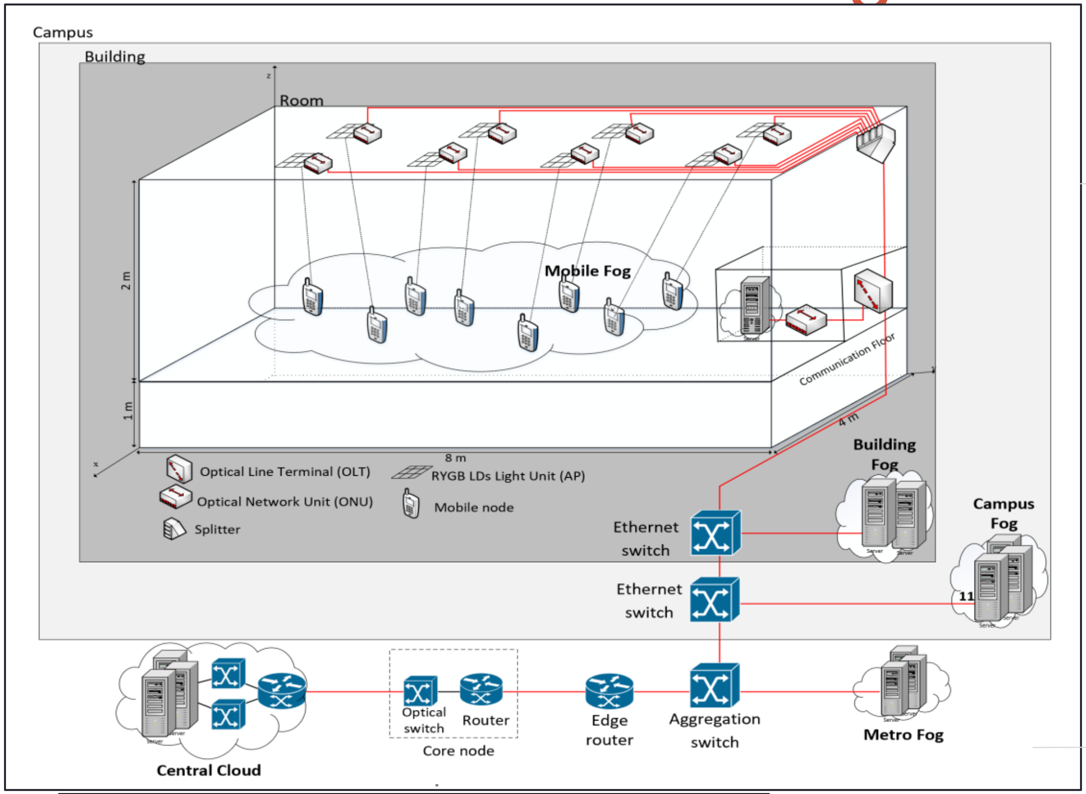

**Energy consumption**

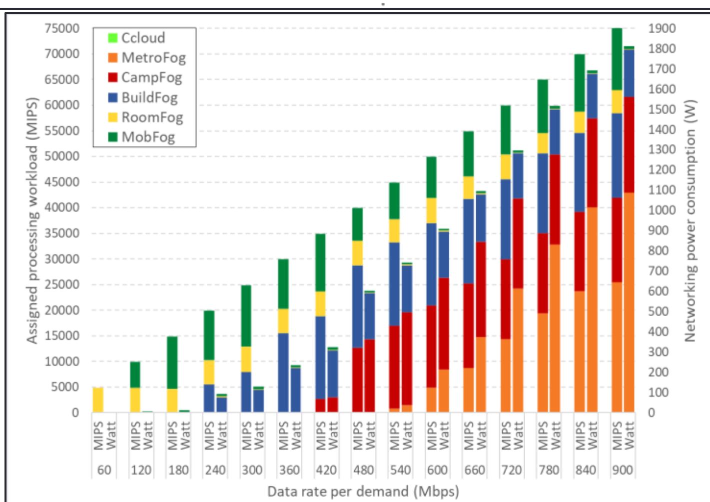



**Completion time**

- For the WDM-TDM architecture, completion time is reduced by about 50% compared to remaining networks while reducing the energy consumption by up to about 88%.
- Future work considers **AP-AWGR wireless links, designing room to room, floor to floor interconnection, and optimizing workloads placement and users mobility**.

# Architecture: Cloud-Fog Processing




## Processing Placement Model

**Objective: Minimize** $\sum_{n \in PN} P_n + \sum_{n \in PN} \mathcal{P}_n$

where $P_n$ is the processing power consumption, given by

$$P_n = \sum_{k \in K} X_{kn} \; E_n \qquad \forall \; n \in PN,$$

$$E_n = \frac{max\ power\ consumption}{max\ processing\ capacity}$$

and $\mathcal{P}_n$ is the networking power consumption, given by

$$\mathcal{P}_n = \sum_{k \in K} L_{ksn} \; \Psi_n \qquad \forall \; n \in PN, \; s \in SN,$$

$$L_{ksn} = F_{ks} \; \delta_{kn} \qquad \forall \; k \in K, s \in SN, n \in PN$$

$$\Psi_n = \frac{max\ power\ consumption}{max\ traffic\ capacity}$$

**The model is subject to the following constraints:**

1- Processing allocation

$$\alpha \; X_{kn} \geq \delta_{kn}$$
$$X_{kn} \leq \alpha \; \delta_{kn} \qquad \forall \; k \in K, n \in PN$$

2- Single allocation (no splitting)

$$\sum_{n \in PN} \delta_{kn} = 1 \qquad \forall \; k \in K$$

3- Processing capacity

$$\sum_{k \in K} X_{kn} \leq C_n \qquad \forall \; n \in PN$$

4- Link capacity

$$\sum_{k \in K} \sum_{\substack{s \in SN \\ d \in PN}} \lambda_{ij}^{ksd} \leq L_{ij} \qquad \forall \; i \in N, j \in Nm_i, i \neq j$$

5- Flow conservation

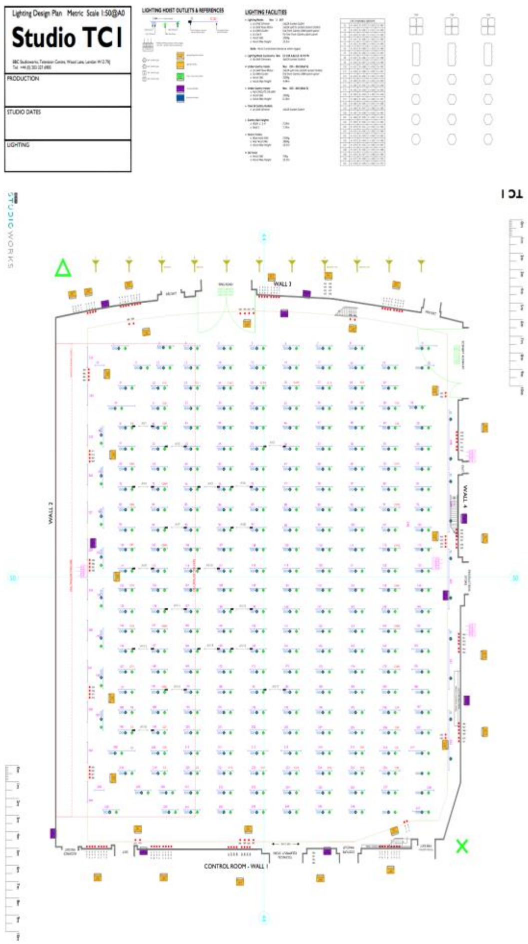
$$\sum_{\substack{j \in Nmi \\ i \neq j}} \lambda_{ij}^{ksd} - \sum_{\substack{j \in Nmi \\ i \neq j}} \lambda_{ji}^{ksd} = \begin{cases} L_{ksd} & if \; i = s \\ -L_{ksd} & if \; i = d \\ 0 & otherwise \end{cases}$$

$$\forall \; k \in K, s \in SN, d \in PN, i, j \in N$$

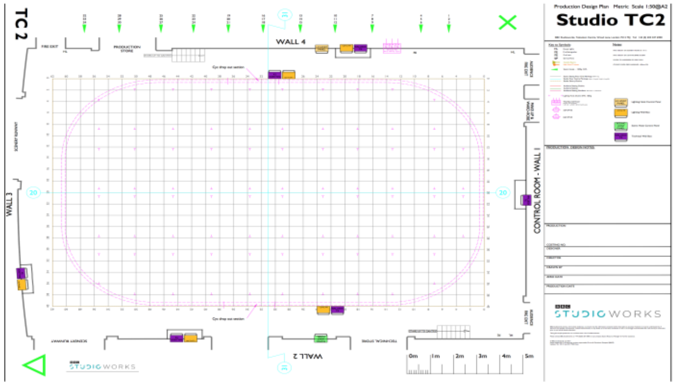
Alsulami, O. Z., Alahmadi, A., Saeed, S. O. M., Mohamed, S.H., El-Gorashi, T.E.H., Alresheedi, M.T. and Elmirghani, J.M.H., "Optimum resource allocation in optical wireless systems with energy efficient fog and cloud architectures," Philosophical Transactions of the Royal Society A, vol. 378, No. 2169, pp. 1-29, March 2020.

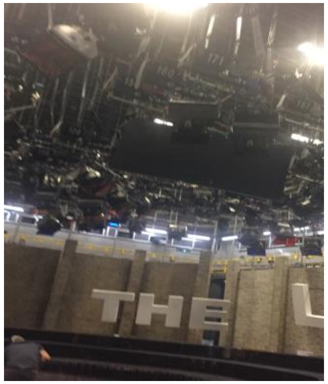
# Demos: BBC strictly come dancing

TOWS
TERABIT OPTICAL WIRELESS SYSTEM





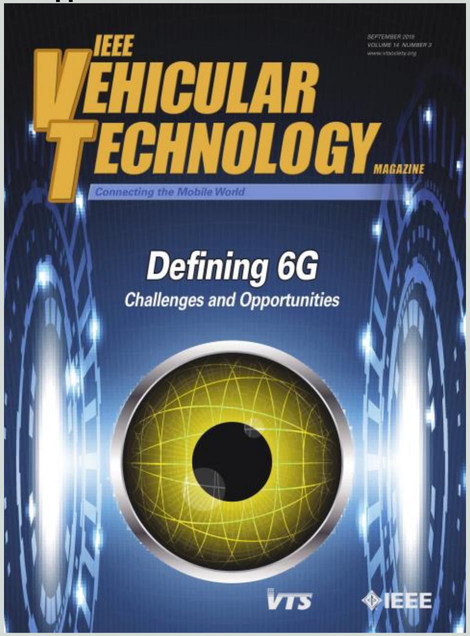


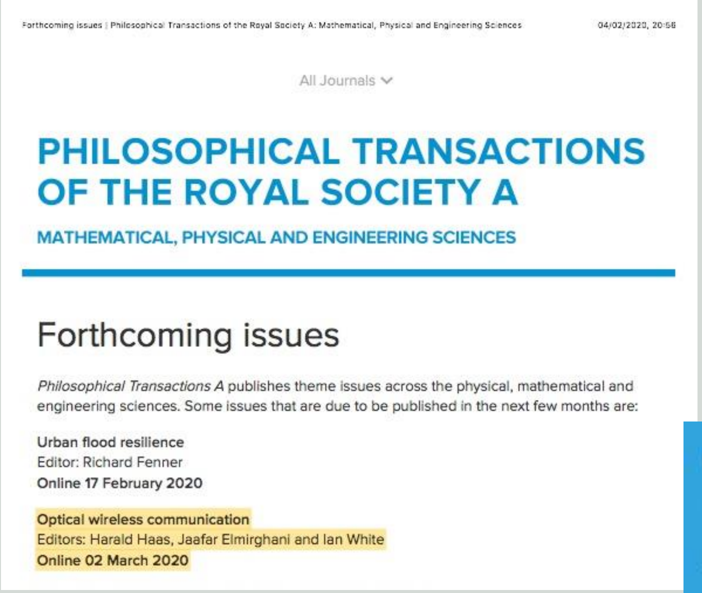



# Long Term Vision for 6G


- Wireless Capacities 2 to 4 orders of magnitude higher than 5G (Tb/s)
- Latencies 1 to 2 orders of magnitude lower than 5G ($\mu$s), autonomous systems
- Intelligence everywhere (machine learning and AI)
- Planet wide coverage (Hetnets and low orbit satellites)


Defining 6G: Challenges and Opportunities





Forthcoming issues | Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 04/02/2020, 20:56

All Journals

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

MATHEMATICAL, PHYSICAL AND ENGINEERING SCIENCES

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*Philosophical Transactions A* publishes theme issues across the physical, mathematical and engineering sciences. Some issues that are due to be published in the next few months are:

**Urban flood resilience**
Editor: Richard Fenner
**Online 17 February 2020**

**Optical wireless communication**
Editors: Harald Haas, Jaafar Elmirghani and Ian White
**Online 02 March 2020**


# Publications: Journals


1. N. Bamiedakis, R. V. Penty and I. H. White, “Carrierless amplitude and phase modulation in wireless visible light communication systems,” accepted for publication in Philosophical Transactions of the Royal Society A, 2019 (invited).
2. X. Dong, N. Bamiedakis, D. G. Cunningham, R. V. Penty and I. H. White, “A Novel Equalizer for 112 Gb/s CAP-Based Data Transmission over150 m MMF links,” accepted for publication in IEEE Journal of Lightwave Technology, vol. 37, pp. 5937-5944, 2019.
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5. Al-Hameed, A. A., Younus, S.H., Hussein, A.T., Alresheedi, M.T., and Elmirghani, J.M.H., “LiDAL: Light Detection and Localization,” IEEE Access, vol. 7, pp. 85645 - 85687, 2019.
6. Al-Hameed, A. A., Younus, S.H., Hussein, A.T., Alresheedi, M.T., and Elmirghani, J.M.H., “Artificial Neural Network for LiDAL Systems,” IEEE Access, vol. 7, pp. 109427 - 109438, 2019.
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9. Haas, H., Elmirghani, J.M.H. and White, I.H., “Introduction to Optical Wireless Communication,” Philosophical Transactions of the Royal Society A, March 2020.
10. M. D. Soltani, M. A. Arfaoui, I. Tavakkolnia, A. Ghrayeb, M. Safari, C. M. Assi, M. O. Hasna, and H. Haas, “Bidirectional Optical Spatial Modulation for Mobile Users: Toward a Practical Design for LiFi Systems,” IEEE Journal on Selected Areas in Communications, vol. 37, no. 9, pp. 2069–2086, Sep. 2019.
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13. E. Panayirci, T. Cogalan, V. Poor and H. Haas, "Physical-Layer Security with Optical Generalized Space Shift Keying", IEEE Transactions on Communications, 2020.
14. Alsulami, O. Z., Alahmadi, A., Saeed, S. O. M., Mohamed, S.H., El-Gorashi, T.E.H., Alresheedi, M.T. and Elmirghani, J.M.H., “Optimum resource allocation in optical wireless systems with energy efficient fog and cloud architectures,” Philosophical Transactions of the Royal Society A, vol. 378, No. 2169, pp. 1-29, March 2020.
15. Elham Sarbazi, Majid Safari and Harald Haas, “The Bit Error Performance and Information Transfer Rate of SPAD Array Optical Receivers,” in IEEE Transactions on Communications, vol. 68, no. 9, pp. 5689-5705, Sept. 2020.
16. Rizwana Ahmad, Mohammad Dehghani Soltani, Majid Safari, Anand Srivastava, Abir Das, “Reinforcement learning based load balancing for hybrid LiFi WiFi networks”, IEEE Access, vol. 8, pp. 132273-132284, 2020.

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22. “Low complexity DSP for high speed optical access networking, Wei, J and Lam, CF and Zhou, J and Aldaya, I and Giacoumidis, E and Richter, A and Cheng, Q and Penty, R and White, I (2021) Applied Sciences (Switzerland), 11
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26. Rizwana Ahmad, Mohammad Dehghani Soltani, Majid Safari, Anand Srivastava, “Reinforcement Learning-based Near-Optimal Load Balancing for Heterogeneous LiFi WiFi network”, IEEE Systems, 2021.
27. Mohammad Dehghani Soltani, Elham Sarbazi, Nikolaos Bamiedakis, Priyanka de Souza, Hossein Kazemi, Jaafar MH Elmirghani, Ian H White, Richard V Penty, Harald Haas, Majid Safari, “Safety Analysis for Laser-based Optical Wireless Communications: A Tutorial”, Submitted to Proceedings of IEEE (17 April 2021).
28. H Kazemi, E Sarbazi, MD Soltani, M Safari, H Haas, “A Tb/s Indoor MIMO Optical Wireless Backhaul System Using VCSEL Arrays”, Submitted to IEEE Transactions on Communications, 2021.
29. N. Bamiedakis, D Cunningham and RV Penty, “Linearisation Method of DML-based Transmitters for Optical Communications, Part I: Theory and Simulation Studies”, Submitted to IEEE Journal of Lightwave Technology, 2021.
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31. Sanaa Hamid Mohamed, Osama Zwaid Alsulami, Taisir E. H. El-Gorashi, Mohammed T. Alresheedi, Jaafar M. H. Elmirghani, "Resilient architectures for free space optical wireless interconnection systems," Proc. SPIE 11692, Optical Interconnects XXI, 1169210 (5 March 2021); https://doi.org/10.1117/12.2577689

# Publications: Conferences


32. N. Bamiedakis, X. Dong, D. G. Cunningham, R. V. Penty and I. H. White, “New Equalizer Structure for High-Speed Optical Links based on Carrierless Amplitude and Phase Modulation,” to be presented at the 22st International Conference on Transparent Optical Networks (ICTON), 2020 (invited).
33. X. Dong, N. Bamiedakis, D. G. Cunningham, R. V. Penty and I. H. White, “A Novel CAP Equalizer for 112 Gb/s Data Transmission over 150 m MMF Links,” in the European Conference on Optical Communications (ECOC), paper P.20, pp. 1-3, 2019.
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41. Alsulami, O.Z., Musa, M.O.I., Alresheedi, M.T., and Elmirghani, J.M.H., “Co-existence of Micro, Pico and Atto Cells in Optical Wireless Communication,” Proc IEEE Conference on Standards for Communications and Networking, Granada, Spain, 28-30 October 2019.
42. Alsulami, O.Z., Alresheedi, M.T., and Elmirghani, J.M.H., “Optical Wireless cabin communication system,” Proc IEEE Con-ference on Standards for Communications and Networking, Granada, Spain, 28-30 October 2019.
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44. M. D. Soltani, Z. Zeng, H. Kazemi, C. Chen, H. Haas, and M. Safari, “A Study of Sojourn Time for Indoor LiFi Cellular Networks,” in Submitted to IEEE 30th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC), Istanbul, Turkey, 2019, pp. 1–6.
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47. E. Sarbazi, M. Safari and H. Haas, “On the Information Transfer Rate of SPAD Arrays,” IEEE Wireless Communications and Networking Conference (WCNC), Seoul, South Korea, Apr. 2020.

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51. Alsulami, O.Z., Saeed, S.O.M., Mohamed S.H., El-Gorashi, T.E.H., Alresheedi, M.T. and Elmirghani, J.M.H., "Resource allocation in co-existing optical wireless HetNets," *invited talk and invited paper at IEEE 22nd International Conference on Transparent Optical Networks* (*ICTON*), Bari, Italy, 19-23 July 2020.
52. Alsulami, O.Z., Saeed, S.O.M., Mohamed S.H., El-Gorashi, T.E.H., Alresheedi, M.T. and Elmirghani, J.M.H., "Data centre optical wireless downlink with WDM and multi access point support," *Proc IEEE 22nd International Conference on Transparent Optical Networks* (*ICTON*), Bari, Italy, 19-23 July 2020.
53. Alsulami, O.Z., Saeed, S.O.M., Mohamed S.H., El-Gorashi, T.E.H., Alresheedi, M.T. and Elmirghani, J.M.H., "Shared optical wireless cells for in-cabin aircraft links," *Proc IEEE 22nd International Conference on Transparent Optical Networks* (*ICTON*), Bari, Italy, 19-23 July 2020.
54. Zeng, Y., Mohamed S.H., El-Gorashi, T.E.H. and Elmirghani, J.M.H., "Delay adaptation method for relay assisted optical wireless systems," *Proc IEEE 22nd International Conference on Transparent Optical Networks* (*ICTON*), Bari, Italy, 19-23 July 2020.
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70. “Novel digital and analogue hybrid radio over fibre system for distributed antenna system (DAS) fronthaul applications”, Tongyun Li, Yumeng Yang, Michael Crisp, Ian H White, Richard V Penty, 2020 Conference on Lasers and Electro-Optics (CLEO): Applications and Technology, pp. JTu2E. 5
71. “Novel compressed digital radio fronthaul over photonically-generated THz wireless bridge”, Tongyun Li, Luis Gonzalez-Guerrero, Haymen Shams, Cyril Renaud, Alwyn J Seeds, Martyn Fice, Ian White, Richard Penty, 2020 Optical Fiber Communications Conference and Exhibition (OFC), pp.1-3
72. “Bending loss improvement and twisting loss studies of flexible multimode polymer waveguides”, F Shi, Nikolaos Bamiedakis, RV Penty, IH White, Daping Chu, Photonics West 2020, Vol. 11286, pp. 112860K
73. A Novel Linearization Method for Optical Transmitters Based on Directly-Modulated Lasers, Nikos Bamiedakis; David Cunningham; Richard Penty; OFC 2021
74. Adnan Qidan, A., Morales-Cespedes, M., Armada, A. G. and Elmirghani, J.M.H., “User-Centric Cell Formation for Blind Interference Alignment in Optical Wireless Networks,” IEEE International Conference on Communications (ICC’21), Montreal, 14-21 June 2021.

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75. Elgamal, A.S., Alsulami, O.Z., Adnan Qidan, A., El-Gorashi, T.E.H. and Elmirghani, J.M.H., “Q-learning algorithm for resource allocation in WDMA-based optical wireless communication networks,” submitted to IEEE 6th International conference on Smart and Sustainable Technologies, SplitTech’2021, 8-11 September 2021, Split.
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78. Adnan Qidan, A., Morales-Cespedes, M., El-Gorashi, T.E.H. and Elmirghani, J.M.H., “Resource Allocation in Laser-based Optical Wireless Cellular Networks,” Submitted to IEEE Global Telecommunications Conference (GLOBECOM’21), Madrid, Spain, 7 -11 December 2021.

# Publications: Whitepapers


79. Taleb, T., Aguiar, R. L., Yahia, I. G. B., Chatras, B., Christensen, G., Chunduri, U., Clemm, A., Costa, X., Dong, L., Elmirghani, J., Yosuf, B., Foukas, X., Galis, A., Giordani, M., Gurtov, A., Hecker, A., Huang, C.-W., Jacquenet, C., Kellerer, W., .... Zorzi, M. (2020). White Paper on 6G Networking [White paper]. (6G Research Visions, No. 6). University of Oulu. http://urn.fi/urn:isbn:9789526226842.

80. Safari, M., Haas, H., Penty, R.V., White, I.H., El-Gorashi and Elmirghani, J.M.H., “Terabit Indoor Laser-Based Wireless Communications: LiFi 2.0 for 6G,” Light Communications Alliance White paper, 2021.

# Publications: Invited Talks

81. Invited talk, Elmirghani, J.M.H., “Future Internet Networks and Systems,” Ofcom, UK, 21 Oct 2020.
82. Invited talk, Elmirghani, J.M.H., “Terabit Optical Wireless Systems for 6G Networks,” EPSRC Towards Ultimate Convergence of All Networks (TOUCAN) Programme Grant final workshop, UK, 4 November 2020.
83. Alsulami, O.Z., Saeed, S.O.M., Mohamed S.H., El-Gorashi, T.E.H., Alresheedi, M.T. and Elmirghani, J.M.H., “Resource allocation in co-existing optical wireless HetNets,” invited talk and invited paper at IEEE 22nd International Conference on Transparent Optical Networks (ICTON), Bari, Italy, 19-23 July 2020.
84. Alsulami, O.Z., Alahmadi, A.A., Saeed, S.O.M., Mohamed S.H., El-Gorashi, T.E.H., Alresheedi, M.T. and Elmirghani, J.M.H., “Optimum Resource Allocation in 6G Optical Wireless Communication Systems,” invited talk and invited paper at IEEE 6G Wireless Summit, Levi, Lapland, Finland, 17-20 March 2020.
85. “A new equalizer structure for high-speed optical links based on carrierless amplitude and phase modulation”, Nikos Bamiedakis, Xiaohe Dong, David G Cunningham, Richard V Penty, Ian H White, 2020 22nd International Conference on Transparent Optical Networks (ICTON), pp. 1-7
86. Invited talk: Elmirghani, J.M.H., “The optical spectrum and Tb/s wireless systems in the 6G era,” UK Department for Digital, Culture, Media and Sport (DCMS) and UK Spectrum Policy Forum (SPF) workshop on Radio Access Network Techniques for 6G, 1 July 2021.
87. Invited talk, Elmirghani, J.M.H., “Terabit Optical Wireless Systems and Energy Efficiency,” UK and Nordic-Baltic Countries 5G Forum, organized by 5G Testbeds and Trials Programme, Department of Digital, Culture, Media and Sport (DCMS), 8 Feb 2021.
88. Majid Safari, “Optical Wireless Communication for 5G and beyond,” The Road Towards 6G Workshop, Indian Institute of Information Technology Guwahati, India, February 2021.